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Original Article

Hybrid fiber and nanopowder reinforced composites for wind turbine blades☆

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ABSTRACT

The results of an investigation into the production of wind turbine blades manufactured using polymer composites reinforced by hybrid (carbon, basalt, glass) fibers and strengthened by various nanopowders (oxides, carbides, borides) are presented. The hybrid fiber-reinforced composites (HFRC) were manufactured with prepreg technology by molding pre-saturated epoxy-strengthened matrix-reinforced fabric. Performance of the manufactured composites was estimated with values of the coefficient of operating condition (COC) at a moderate and elevated temperature.

1. Introduction

At present, a major problem in the power industry is to increase the amount of electricity manufactured from wind in the world energy balance to 12% by 2020, on the basis of a gain of 25–30% in the rated capacity per year. Small-scale power developed in microgrid systems plays a significant role in the power supply of developing countries, as well as in the rural and remote regions of any country. Development of environmentally friendly small-scale power, focused on the private consumer, requires an increase in the efficiency of wind turbines and the reduction of their cost, as well as stable provision of energy at moderate wind speed. The power efficiency and the cost of a wind turbine vary considerably and are primarily defined by its main elements – blades and a wind rotor.

The need to increase the efficiency of wind turbines at low wind speeds has led to the development of a number of special programs in various countries. One example of this type of program is the US Small Wind Turbine Industry Roadmap, a 20-year industry plan for small wind turbine technology.

In 2006–2008, the Science and Technology Center in Ukraine financed the project "The small wind turbine of the raised efficiency at moderate winds with adaptive aero elastic blades from composite high-modular materials" (Project Manager Dr. N.P. Ushkin, State Design Office, National Space Agency of Ukraine).

The main objective of the project was the development of a small wind turbine, energetically more effective than current models (by 30–50%) at prevailing moderate wind speed (4.0–6.0 m/s) and with a reduced specific cost (by 30–50%). This was based on the use of a new design for the blade, a decrease

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in the threshold of activation of the turbine (from 2.5 to 3.5 m/s to 2 m/s), and a decrease in magnitude of anticipated wind speed (from 12 to 14 m/s to 9–10 m/s), as well as the application of a new hybrid composite for the turbine blade. To perform the material testing needed for the project, i.e., the development of a new composite for the turbine blade, the Frantsevich Institute for the Problem of Materials, part of the National Academy of Sciences of Ukraine (Project Manager, Dr. L. R. Vishnyakov) and the Mining Institute of the Academy of Sciences of Georgia (Project Manager, Dr. N.M. Chikhradze) were engaged. In the present paper, the main results were obtained at the Mining Institute. To perform the objectives of the project, the authors were guided by the current belief that the application of blades rigidly fixed in a nave is the modern technical solution allowing for simplification of the design and increasing the reliability of the system. However, the adaptive blades demand the use of very expensive carbon fibers to ensure the required rigidity and elasticity of the blade. In the material testing performed, a novel choice was made to use a new material for the adaptive blades, partially replacing the expensive carbon fiber, which will considerably reduce (30–35%) the blade cost.

Currently for the production of hybrid blades, carbon and glass fibers are mainly used as the basic materials [1]. Additionally, studies on reinforcing the epoxy matrixes using basalt and other fibers [2] have been performed. The present authors attempted to achieve the aforementioned purpose using composites of hybrid reinforcing fibers (carbon–basalt, carbon–basalt–glass) and polymeric matrixes with high-modular fillers (fibers, powders). The results from these investigations have recently been published [3–6].

2. Experimental

2.1. Experiments on composite matrix strengthening

The current investigation utilized epoxy-diane resin with passive diluents – using dibutyl phthalate at 15 m.f. per 100 m.f. of resin. The resin has a density of 1.168 g cm^{-3}, and its viscosity at 20 °C is 120 P. The resin's components were epoxy groups at 17 mass%, total chlorine at 0.85 mass%, chlorine ions at 0.007 mass%, volatiles at 0.85 mass% and the time of gelation of the resin at 100 °C was 3.0 h.

To reinforce the epoxy resin, powders of boron carbide (100 μm), silicon carbide (80 μm) and zirconium diboride (100 μm), as well as mullite-like oxide crystals $3Al_2O_3{\cdot}2SiO_2$ (diameter 2–8 μm, length 80–200 μm), basalt powder (100 μm) and diluvium powder (60 μm) were used. The diluvium powder had the following chemical composition: SiO_2 – 57.5; Al_2O_3 – 19; Fe_2O_3 – 7.4; CaO – 1.1; MgO – 3.0; R_2O – 5.2. For production of boron carbide, amorphous boron and technical carbon were used as ingredients. The prepared mixture was briquetted in a graphite mold. Boron carbide was synthesized in a vacuum electric furnace. Synthesis was performed at 1850 ± 25 °C for 2.5 h. Cooling was performed under vacuum over 10 h. Zirconium diboride was produced using the method of boron carbide reduction. Zirconium dioxide and carbide were preliminary processed under vacuum for charge production. Mullite-like crystals were prepared using the method of oxide solution crystallization in a melt bed. Basalt powder preparation included the following operations: crushing of basalt stones at the hydraulic press; melting; crushing and grinding of ingots; fractionation of the ground powder in a high energetic "Fritsch" planetary premium line ball mill. The used diluvium powder was dispersive, loose, anthropogenic raw material.

The amount of powders added to the epoxy resin was 7% of the resin mass. The hardener used for the compositions was polyethylene polymine (12% of the resin mass).

The following samples were prepared: "a" – pure epoxy resin, "b" – with diluvium, "c" – with boron carbide, "d" – with silicon carbide, "e" – with $3Al_2O{\cdot}2SiO_2$, "f" – with ZrB_2 and "g" – with basalt. The samples were molded under tension in the form of mortar briquettes of 50 mm × 4 mm × 2 mm dimensions. Strips of 170 mm × 15 mm × 3 mm for fatigue testing were prepared as well.

Short-term mechanical tensile tests were conducted using an FPZ-100 machine with automatic recording of strength-deformation. The tensile machine's maximum load was 1.0 T using a test velocity of 15 mm/min. The reinforcement coefficient of the composites was evaluated by comparison with the strength and deformation results of the pure epoxy resin.

For material testing on fatigue bending, the device shown in Fig. 1 has been used. The main parameters of the device are: the simultaneous testing of three sheets or samples; a bending angle from 20° to 180°; clamp width of samples up to 30 mm; weights for preliminary load from 0.2 to 5 kgf; number of bends per minute – 100; three individual counters with an automatic shut-off at sample breakage.

As shown in Fig. 1, each specimen was fixed in a special grip that swings about its axis of rotation. The grip is designed so that the band axis coincides with the rotation axis, and the specimen is repeatedly subjected to a load imposed by hanging weights. This is associated with a definite preliminary tension. For this study, the bending angle was selected as 20°, the load was 2 kgf, and the number of the bends per minute was 100.

An endurance coefficient was determined from appropriate compositions (series "d","g"), with regards to reinforcement. The endurance coefficient signified a ratio between the residual strength of the composition after cyclic testing and its short-term static strength. The magnitude of this ratio, which reduces slightly regardless of number of cycles (*N*), was used as the endurance coefficient.

Fig. 1 – Device for testing on fatigue.